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DESIGN CONSIDERATIONS FOR POLARIMETRIC RADARS TO MEASURE BACKSCATTER FROM HYDROMETEORS

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ABSTRACT

The measurement of backscatter from hydrometeors imposes specific requirements on polarimetric radar systems and components. We begin with an overview of the target characteristics. We describe the measurable quantities pertinent to each of several measurement schemes and present estimates of the accuracy with which these quantities should be measured. We discuss the required characteristics of a radar designed to measure the specified quantities. Our primary focus is on measurement schemes employing orthogonal basis vectors. We discuss briefly the tolerable error levels of schemes involving non-orthogonal basis vectors.

1. INTRODUCTION

This paper is intended to shed light on present knowledge of the design and construction of polarimetric radars for meteorological applications. We discuss the characteristics of the medium, the errors associated with the measurements, and the required characteristics of the radars. We attempt to codify the various measurement schemes in terms of the measured quantities, analytical procedures, and desired accuracies. We discuss some previously published results, such as those of McCormick and Hendry [1, 2], in terms of radar hardware requirements. Thus the present paper is a collection of notes to aid the designers and users of these systems. With the present state of knowledge, however, it is not possible to reach a simple "this is how it's done" conclusion.

2. TARGET CHARACTERISTICS

Meteorological backscatter media comprise many small diverse scatterers in random relative motion due to turbulent air motion and fall speed differences. For meteorological purposes one is nearly always concerned with their characteristics on time scales long enough to permit statistically meaningful averages of the measured and derived quantities and short enough that the particulate content of the sample volume is not significantly changed. Many of the details of reflectivity measurement, which are discussed, for example, by Battan [3], are related to other measurable quantities. The shorter time limit is frequency dependent and ranges from a few hundredths of a second at K_a-band to a few tenths of a second at S-band. The longer limit depends of air motion and fall speeds and is typically a few seconds. One usually works near the shorter time limit because of the typical need to scan a volume of space rapidly and repeatedly.

The raindrops, ice crystals, snowflakes, and hailstones, collectively referred to as hydrometeors, can often be approximated by a collection of spheroids having a distribution of shapes and a distribution of orientations about some mean orientation angle. Rain, for example, is a highly oriented medium, as the oblate spheroidal drops tend to be aligned with their symmetry axes vertical, with a

standard deviation of a few degrees. Ice particles tend to be more randomly oriented, except when influenced by electric fields in clouds. In a complete polarimetric measurement one seeks information about the average shape, the distribution of shapes, the average apparent orientation or canting angle, and the distribution of canting angles. This information is then used to infer other quantities and characteristics, such as size distribution, thermodynamic phase, precipitation rate, or water content. When using a non-coherent polarimetric radar, one interprets the measurements in terms of the dominant type of hydrometeor within the radar sample volume. Coherent reception of all the backscattered signals provides additional information that permits identification of multiple types of hydrometeors within the radar sample volume [4], but the description of these measurements is beyond the scope of this paper.

The dynamic range of signals backscattered from meteorological targets is large, because of the wide variation of reflectivity from non-precipitating ice clouds to severe convective storms and the wide domain of range within which these phenomena may occur. Meteorological targets typically fill the main lobe and the copolarized and cross-polarized sidelobes of a radar beam and sometimes extend to the backlobe. Hence the design of the antenna and radome is critical to the acquisition of high-quality data.

3. POLARIMETRIC MEASURABLE QUANTITIES

The complete polarimetric measurement requires at least the transmission of two orthogonal polarizations in rapid succession and the simultaneous reception of two orthogonally polarized signals. Such a measurement yields the four complex terms of the scattering matrix, from which the autocovariances and cross-covariances can be computed. Some of the resulting quantities have been extensively analyzed and measured, but the physical significance of others is obscure. Hence, most polarimetric meteorological radars have been designed to measure only a few of the possible quantities. For practical reasons, most of these systems employ either linear or circular polarization basis vectors, and this choice defines the two major categories discussed in Section 4.

A compilation of the polarimetric backscatter measurable quantities, calculated parameters, associated accuracies, and error contributors for the various system types is presented in Figure 1. The figure is by no means complete; it is an attempt to bring order out of chaos. A quick review of this diagram reveals that for some basis vectors there are no established accuracy requirements and associated system error limits. Furthermore, and perhaps more fundamental, there is a lack of connecting paths between the results that are acquired by the various types of radar systems employing differing basis vectors. Not only are most of the data and most of results non-transportable between measurement schemes, but the comparable measurement accuracies are unknown. The problem of transforming quantities measured with linear polarization to quantities measurable with circular polarization and *vice versa* has recently been discussed in the meteorological literature [5], but there remain unsolved issues. Finally, the value of any additional knowledge that might be supplied by the use of an alternative set of basis vectors to allow a lesser measurement accuracy is undetermined. These items should be addressed in the future, as they may impact results as well as system cost.

The terms employed in Figure 1 and elsewhere are explained in Table 1. The notation is consistent with that of several key references [1, 2, 6, 7, 8], a working knowledge of which is almost a prerequisite to entering the polarization diversity meteorological radar business. Reference [6] is especially useful as it is a compendium of the state of the art in polarization diversity radars for meteorology. In Figure 1 and Table 1 R_1 and R_2 denote the received amplitudes in the transmission and orthogonal channels respectively. The corresponding power ratio is given by

$$K_{22}/K_{11} = \langle R_2 R_2^* \rangle / \langle R_1 R_1^* \rangle . \qquad (1)$$

With linear polarization basis vectors, Equation (1) defines the linear depolarization ratio (LDR); with circular polarization basis vectors, it defines the cancellation ratio, which is the inverse of the circular depolarization ratio.

Table 1. Parameters used in polarimetric error analysis.

Antenna parameters	
$G_1(\psi,\chi)$, $G_2(\psi,\chi)$	Copolarized amplitude antenna pattern of polarizations 1 and 2, measured in the angular coordinate system defined by ψ and χ.
$\Phi_1(\psi,\chi)$, $\Phi_2(\psi,\chi)$	Copolarized phase antenna pattern of polarizations 1 and 2, measured in the angular coordinate system defined by ψ and χ.
β_{12}	Copolarized overall antenna pattern inequality factor.
D	Diameter of main reflector
f	Focal length of main reflector
System parameters	
α	Apparent canting angle of hydrometeors.
ε	Complex-valued one-way polarization error (isolation) term representing the leakage of copolarized energy into cross-polarized radiation (or reception). Varies over the antenna pattern; may be a function of the antenna pointing angle or of the target.
$\bar{\varepsilon}$	The mean value of ε. See f, below.
ρ	Equivalent fraction of scatterers having a common orientation.
ϕ_{12}	Receiver or system interchannel phase angle.
f	Complex-valued overall one-way polarization error (isolation) term. Represents the entire system, whereas ε may represent error quantities associated with particular components.
i	Term representing the fraction of copolarized energy that is radiated. Defined by conservation of energy, $i^2+\|\varepsilon\|^2=1$, if absorptive (ohmic) losses are ignored.
R_1, R_2	Output signal level from receiver channels 1 and 2.
R_1^H	Output signal level from receiver channel 1 configured for horizontal polarization.
$ICPR_1$, $ICPR_2$	One-way and two-way integrated cross-polarization ratio. An antenna or radar performance parameter independent of polarization basis vector. $ICPR_1$ defined as ratio of total cross-polarized (unwanted) energy to total copolarized (desired) energy radiated by the antenna (integrated over 4π steradians). $ICPR_1$ is measured on an antenna range, whereas $ICPR_2$, which is 6 dB "worse," must be used to characterize monostatic radar performance.
ICR	Integrated cancellation ratio. Defined similarly to ICPR, but for circular polarization only.

Table 2. Radar performance specifications for measurement of differential reflectivity and circular depolarization ratio.

Parameter	Diffl. Reflectivity	Circ. Depol. Ratio
$ICPR_1$ or ICR_1	-26 dB	-40 dB
Isolation	-20 dB	undefined
Amplitude tracking	not applicable	1.0 dB
Phase tracking	undefined	<1.0°
Pulse-to-pulse amplitude error	≤0.2 dB	undefined

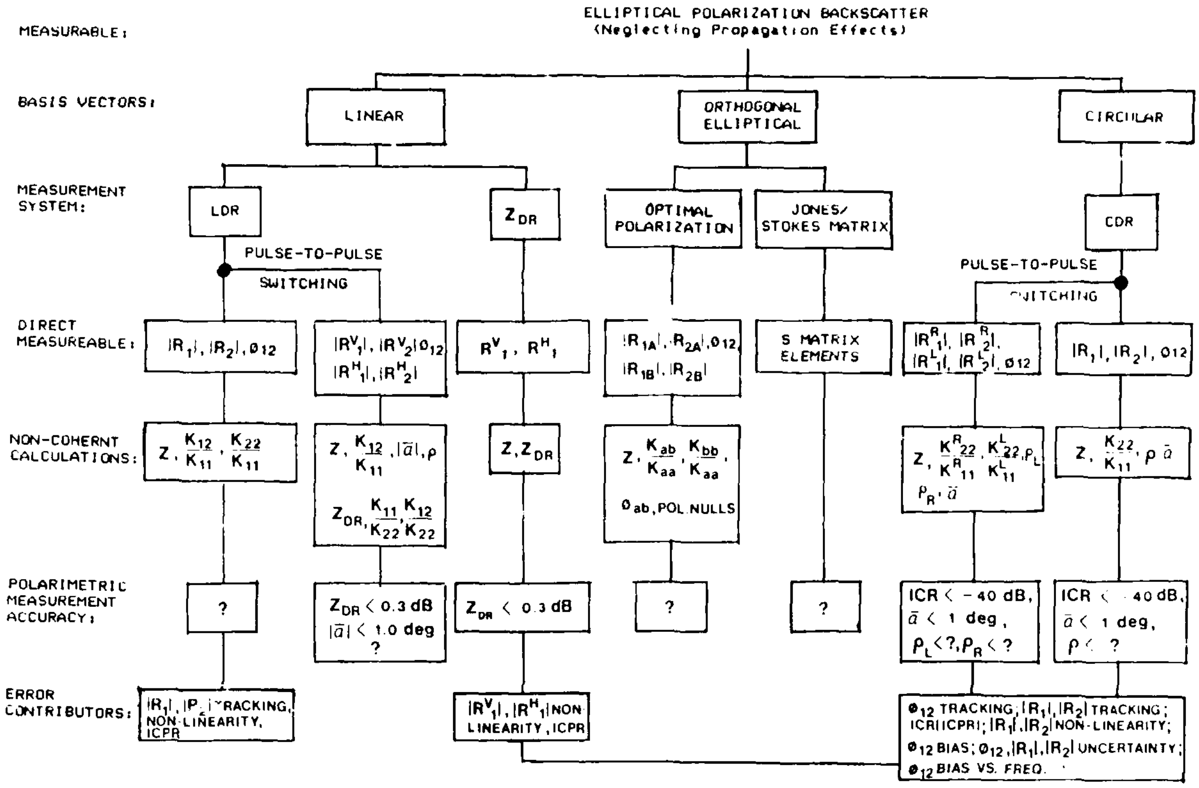

Figure 1. Measurable quantities and error quantities pertaining to elliptical polarization backscatter.

4. POLARIMETRIC METEOROLOGICAL RADAR SYSTEMS

4.1. LINEAR POLARIZATION

In the majority of systems using linear basis vectors the transmitted signal is switched between horizontal and vertical polarization on successive pulses, and only the co-polarized backscattered signal is received. The cross-polarized signal in these systems is discarded into a termination within the antenna polarizer or microwave switch assembly. This radar configuration has been discussed by Seliga and Mueller [9] and Bringi and Hendry [6]. The polarimetric quantity most commonly obtained from such a radar is the ratio of the power received with horizontal polarization to the power received with vertical polarization, known as the differential reflectivity and denoted by Z_{DR} [10]. In decibel notation, this ratio lies between -2.5 dB and +5.0 dB for most meteorological media. Because the domain is small, it must be measured with accuracy of a few tenths of a decibel for useful interpretation. Hence the required polarization switching must occur at a time scale much less than the signal decorrelation time. Although the cross-polarized signal is not measured, the cross-polarization error generated by the radar has an impact on the accuracy of the measurement, as will be discussed below.

An important subcategory of linear polarization radars comprises those with dual receiver channels. If operated without a fast switch, these yield the linear depolarization ratio (LDR) and the relative phase of the two received signals. With a fast switch, these yield the complete linear polarization scattering matrix.

4.2. CIRCULAR POLARIZATION

Meteorological radar systems that employ circular polarization basis vectors receive both the copolarized and cross-polarized backscattered signals. The power or amplitude in each channel and the phase difference between the two signals are essential to determine hydrometeor characteristics. Transmission typically occurs on only one polarization. While burst-to-burst transmitted polarization switching may be possible, it is usually not performed. McCormick and Hendry [2] provided a useful discussion of the technique. The circular polarized system can also be

operated with a fast switch to measure the entire scattering matrix, but usually this is not the case.

The dominant measurement of the circular polarized radar is the ratio of the power received in the channel of transmission to the power received in the orthogonal channel. This quantity, known as the circular depolarization ratio (CDR) is the inverse of the "cancellation ratio," which refers to the suppression of rain "clutter" in surveillance and tracking radars. There is insufficient space in this paper to discuss the many other parameters which are directly measured or determined from the data provided by the CDR radar. More detailed discussion is provided by Bringi and Hendry [6]. Because hydrometeors are usually spheroidal to a good approximation, the energy returned to the channel of transmission can be small; CDR varies typically between -15 dB and -40 dB.

4.3. AGILE POLARIZATION

A unique radar that combines all the capabilities of the aforementioned systems was constructed by Enterprise Electronics Corp. of Enterprise, Ala., for Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR) in West Germany [11]. With a combined fast switch and polarizer assembly, it can measure the backscatter matrix with either linear or circular polarization. In addition, this radar has the unique capability to measure optimal polarization vectors by varing the transmitted polarization vector over 64 states and receiving both the transmitted and orthogonal polarization states.

5. ACCURACY REQUIREMENTS

Some of the system accuracy requirements of the Z_{DR} and CDR radars have been understood or presumed to be understood for the past few years. These requirements, shown in Table 2, are not rigid specifications, but are engineering goals. The demands on the engineer are that the phase and amplitude resolution of the channels, the isolation between channels, the tracking within and between the channels, and the induced error levels of the radome, antenna, receiver, and microwave package be as nearly perfect as possible. As each of these items is improved, the data acquisition capabilities of the system is improved.

We should note that as the imperfections of the system are reduced, the radar becomes increasingly more useful in discriminating between the various types of precipitation. A radar with moderate performance characteristics is useful for some tasks, but it will not provide all the data that a high performance system can. For example, if the integrated cancellation ratio of the circularly polarized radar is on the order of 25 dB, differentation between hail and rain would be possible, while differentation between light rain and drizzle would not. For the latter purpose, an ICR of about 40 dB is required. At present there is no known set of performance parameters beyond which further system improvement provides no additional data.

6. COMMENTS ON POLARIMETRIC ERROR ANALYSIS

Unfortunately, a discussion of the design considerations of a polarization diversity radar must include a section on error analysis before describing the design mechanics unique to the radar. Much of the error analysis work, expressed in terms of multiply subscripted Greek letters, appears to have come from a mystical fraternal organization. Be assured that this is not the case. The published error analyses [2, 7, 8] are sincere attempts to define the domains and accuracies of measurable quantities and to relate these to affordable radar components and systems.

Two approaches of error analyses can be taken: (1) the basic approach wherein each radar element, i.e., microwave package, antenna, etc., is taken as a stand-alone entity with its limited set of errors or uncertainties and (2) a global approach wherein the radar, as a whole, is considered with each individual element contributing to an entire set of errors and uncertainties. While the former can lead to the reduction of error magnitudes and improvement of the overall measurement accuracy, the latter considers component interaction. Because of the extreme accuracy demanded of a polarimetric meteorological radar, only a global or system approach makes sense. We shall examine several of the system components with this view in mind.

The purpose of Table 1 is to guide the engineer through terms and concepts that may be unfamiliar. Readers having some familiarity with the referenced papers may skip the remainder of this section and Table 1.

6.1. AMPLITUDE ANTENNA PATTERN

The term "amplitude" refering to the normal antenna pattern in this paper and elsewhere in the literature should not be confused with the parameter "amplitude" used in the field equations of McCormick [7]. There the received field equations correctly contain the antenna amplitude pattern as $G^{1/2}$.

6.2. MEAN VALUE OF ERROR QUANTITIES

The mean value of some error quantities might describe fundamentally different relations than the point values of these quantities. For example, β, an antenna error term encompassing both the amplitude and phase patterns has an angular dependence in the ψ and χ coordinate system. However, the mean value of β describes antenna inequalities independent of target location or distribution in the antenna coordinate system. One would expect, in a well designed system, that $\overline{\beta}$ would be very close to unity, but β is not necessarily close to unity at any antenna observation angle. McCormick (personal communication) suggested a similar effect for ε. Furthermore, for a well designed system, one assumes $\overline{\beta^2_{12}} \approx 1$, and that ε_1 and i_1 are separable. In this case $\overline{\varepsilon_1}$ becomes the global term, f, which we described in the proceedings of the 1983 Workshop on Polarimetric Radar Technology [12] and which, if small, approximates the one-way ICPR. These errors divide naturally into those for which $\overline{\varepsilon_1}$ is non-zero and those for which the variance of ε_1 is non-zero. The former are angularly independent and may be reduced by means of microwave trimming networks or in software, while the latter are angularly dependent and usually cannot be removed without *a priori* knowledge of the target. A non-zero value of $\overline{\varepsilon_1}$ can be a manifestation of antenna misalignment, insufficient feed phase flatness, subreflector alignment, or surface errors. Variation of ε_1, on the other hand, can be caused by support structure design, type and symmetry of feed, or gravitationally-induced distortion of the main reflector.

The antenna pattern inequality term $\overline{\beta^2_{12}}$ assumes angular independence. However, this may be only true for high elevation angle observations. For observations close to the horizon, the elevation amplitude and phase antenna patterns can be significently distorted by ground reflections. Here only *in situ* measurements can determine the antenna patterns. A well designed system may have some observation directon for which the affect of reflections is maximized and for which only a reduced polarization isolation is attainable.

7. SOURCES OF POLARIMETRIC ERROR

The significant sources of error are located in the receiver, microwave package, and antenna. The transmitter can contribute unwanted cross-polarized radiation by virtue of a mismatch at the transmitter-polarizer interface. The degree of this mismatch and severity of cross-polarization can be determined from VSWR measurements. We offer further comments on this relationship below.

Three fundamental quantities exist which contribute to polarimetric error: isolation, amplitude tracking and phase tracking. Each of these is directly related, by means of the error parameters, to the geometry of the measurement, the target, and the radar components. These quantities are also interrelated; for example, a greater amount of polarization isolation than initially anticipated may be required for detailed observations of a particular target because of the off-axis cross-polarization induced by an adjacent highly depolarized target. This effect may be further aggravated if the cross-polarized sidelobe level of the antenna pattern exceeds the copolarized level at specific angular displacements from boresight. The designer's initial perception is that only the antenna system errors generated within the antenna components ought to be considered. However, consideration of the geometry of the measurement must also be included.

While an understanding of the error due to measurement geometry is relatively straightforward, the understanding of target-induced error is subtle. This error can be described as a coupling of two error parameters by the target. For example, Metcalf and Ussailis [8] discussed the effect of mean apparent canting angle on the relationship of one-way ICPR to the error of differential reflectivity. Note that the canting angle is not measurable with a "differential reflectivity" radar. Further calculations of target-induced error have yet to be presented.

Errors induced by components include those due to the antenna, microwave package, receiver, and digital signal quantization. Some sources of component-induced error and associated effects are presented in Table 3. The remainder of this section will be devoted to those component details that are specific to polarization diversity radars.

Table 3. Some sources of error and associated effects.

Source of error	Effect
<u>Radome</u>	
Cover material	Slight signal absorption; reflection of energy into antenna and polarizer.
Spars	As above, plus increased copolarized and cross-polarized sidelobes.
<u>Antenna</u>	
Subreflector	Increased copolarized sidelobes due to aperture blockage.
Spars	Increased cross-polarized sidelobes.
Subreflector and main reflector surface irregularities	Increased copolarized and cross-polarized sidelobes; increased on-axis cross-polarization.
Small f/D ratio	Increased linear cross-polarization in axisymmetric systems without a Huygens source feed.
Location and number of spars	Reduced cross-polarization for even number of spars and attachment near rim of main reflector.
Deviation from Huygens source feed	Increased linear cross-polarization due to unequal TE_{11} and TM_{11} modes launched from feed.
Lack of circular symmetry of feed	Cross-polarization due to unequal TE_{11} and TM_{11} modes. Circular symmetry necessary to launch equal TE_{11} and TM_{11} modes in all planes.
Misalignment of antenna components	Increased copolarized and cross-polarized sidelobes; decreased depth of nulls; decreased overall gain; increased beamwidth.
<u>Microwave package</u>	
Mismatch between polarizer and feed or between polarizer and RF switch	Overall cross-polarization level proportional to return loss of mismatch.
Waveguide between polarizer and feed	Phase error may be introduced when ambient temperature changes.
Phase shifter tracking errors in RF switch or temperature change in RF switch	Decreased polarization isolation; interchannel amplitude and phase mistracking.
Interchannel phase mistracking correction greater than 2π	Isolation becomes dependent on microwave frequency and on bandwidth occupied by transmitted pulse.
<u>Receiver</u>	
Interchannel phase mistracking correction greater than 2π	Phase tracking, and perhaps amplitude tracking, become frequency dependent.
Insufficient interchannel local oscillator isolation	Decreased polarization isolation.

7.1. RADOME

The radome will influence the antenna amplitude and phase pattern. Gupta and Claydon [13] have published some theoretical analysis on the phase and amplitude distortions introduced by space frame radomes. Their measurement results, however, are suspect due to the influence of a fiberglass supporting structure employed in the measurement. There is no microwave transparent material that will not distort these measurements. More effort is required to develop a theoretical understanding of the distortion introduced by the radome on the phase and amplitude antenna pattern.

7.2. ANTENNA

7.2.1. Cross-polarization and Sidelobes

The cross-polarization contribution of the antenna have been discussed at length in the past [6, 14]. Key points of these discussions are:

(1) Cross-polarization is not a function of the antenna f/D, as such, but is related to the manner in which the feed is viewed, off-axis, by the reflector. In the case of a linear feed, i.e., a dipole, increasing the reflector f/D reduces the cross-polarized energy that is seen by the reflector.

(2) Cross-polarization induced by the feed in either linearly or circularly polarized systems can be theoretically eliminated by the use of a Huygens source feed. This type of feed represents a class of circular antennas that radiate the HE_{11} or hybrid mode. Potter horns and corrugated horns are typical examples of such a feed.

(3) For an axisymmetric reflector antenna a symmetric quadrapod feed support structure or subreflector support structure that is attached near the rim of the reflector, where the reflector illumination is reduced, is essential to decrease the radiation of residual cross-polarization induced by the feed and spars. A recent discussion of this subject is that of Kildal et al. [15]. For circular polarization the absolute magnitude of the cross-polarized sidelobe levels, when all the aforementioned attributes are employed is approximately 8 dBi, independent of reflector diameter [16].

(4) An offset reflector antenna can be designed to significently reduce copolar sidelobes by eliminating blockage and to reduce cross-polar sidelobes by employing a double off-set configuration [17]. Unfortunally an offset reflector antenna can cost considerably more than an axisymmetric antenna.

7.2.2. Copolarized and Cross-polarized Antenna Pattern

According to Ludwig [18], three coordinate systems are commonly utilized to measure the copolarized and cross-polarized antenna patterns. For polarimetric meteorological radar antennas, only the so called "third definition of Ludwig" is applicable. The use of elevation-over-azimuth antenna pattern recording equipment provides antenna patterns which correspond to this definition. With the commonly employed coordinate systems, azimuth-over-elevation equipment can couple copolarized source energy into the cross-polarized pattern of the antenna under test.

7.2.3. Antenna Phase Pattern

The antenna phase pattern is not usually measured and is not discussed at length in the literature. Deviations from a flat phase pattern can be caused by displacement of the feed phase center from the focal point, deviations of the main reflector or subreflector surfaces from their required shape, random errors of the refelector surfaces and departure of the feed wavefront from a spherical shape [19]. Obviously, two phase distributions can exist: a uniform phase error between polarizations for the antenna as a whole or a distribution of phase fluctuations within the aperture.

7.2.4. Surface Roughness

Another source of error affecting the cross-polarized level is surface imperfections. The antenna is considered to contain a few large correlated areas; the RMS values or peak values of the surface error within the correlated area are analyzed to determine the anticipated cross-polarized levels. A correlated area may be considered to be the area of one of the refelector panels. Although cross-polarization induced by surface roughness has just begun to be understood in

the theoretical context, it appears that a reasonable maximum surface roughness value for an S-band (10-cm) linear polarization diversity radar is 1.3 mm (0.050 inch) RMS, which is an achievable value.

7.3. MICROWAVE PACKAGE

While the isolation ratio, absolute magnitude, and intrachannel phase can all be affected by the microwave package tolerances, polarimetric isolation is the only quantity that is difficult to improve. Amplitude and phase tracking errors in dual-channel systems will, after a suitable warm-up, be slowly varying functions of ambient temperature and system aging and can therefore be conveniently trimmed prior to observation and during maintenance periods. In single-channel systems, amplitude measurement errors can be mitigated in software. The degree of polarization isolation, however, is subject to phase imbalance, amplitude imbalance, and component isolation internal to the polarizer, the high speed RF switch, or both.

7.3.1. Polarizer

Although single-channel systems do not ulitize the cross-polarized component of the electric field, with the possible exception of the Chilbolton radar in the United Kingdom, they all generate cross-polarization within their polarizers. This component is radiated and received into a termination. We have shown that this cross-polarization can have a significant effect on the accuracy of the measurement of discrete targets [12] and meteorological targets [8].

Fortunately, this type of polarizer can be mathematically analysed as a short-slot hybrid coupler. Riblet [20] performed the definitive analysis on the coupler. He showed that the intrachannel isolation as well as amplitude imbalance and phase imbalance through a hybrid coupler are totally functions of the reflected energy as seen by each port of the coupler. The reflected energy is measured as "reflection coefficient" or as the "return loss" at each of the microwave junctions attached to the coupler ports. These parameters are related to the voltage standing wave ratio (VSWR) through a simple equation (see Section 7.3.4 below). Hence, a one-to-one correspondence exists between the coupler parameters and the VSWR on each arm of the coupler. In the case of circular polarization the reflections created at the antenna ports re-enter the polarizer and are reflected at ports internal to the microwave package. This retransmitted energy undergoes a 90° phase shift within the polarizer and exits the antenna as unwanted cross-polarization. In the case of linear polarization, the reflected signal may be transmitted as an unwanted cross-polarization or may be reradiated with a 180° polarimetric phase change and appear as copolarization.

7.3.2. Microwave Switch

With one exception, every high-power RF switch design presently utilized in polarization diversity radars either is an integral assembly of a mechanical switch and polarizer or comprises a separate polarizer and an electronic switch assembly. The latter contains two or more electrically driven ferrite phase shifters within a microwave circuit to provide the switched paths. Although there are two notable exceptions, the mechanical designs are generally implemented on two-channel systems that do not require pulse-to-pulse switching speed.

The disadvantage of the ferrite switch is its high cost and the change in its characteristics as a function of pulse duration, peak power level, average power level, and temperature. Of the two significent ferrite phase shifter designs, the rotary type manufactured by Microwave Applications Group, Santa Maria, Calif., has phase and amplitude deviation characteristics that are easy to control and can operate at relatively high duty cycle levels, but can withstand only a modest peak power level. The slab-type phase shifter manufactured by Raytheon Co., Northboro, Mass., and Electromagnetic Sciences, Inc., Norcross, Ga., has phase and amplitude characteristics that are more difficult to control; it can withstand much higher peak power levels but at the cost of a lower duty cycle. Because of the peak power requirement only the slab ferrite phase shifter has been employed in meteorological radar applications.

A schematic of the ferrite switch, also known as a four-port switchable circulator, is given in Figure 2. Because of the power level and isolation requirements demanded of the switch, the device is not only non-reciprocal, it is not anti-reciporal. Assume that the switch is set in the forward state so that the transmitted energy entering Port 1 will be completely sent to Port 3, and the energy exiting through Port 4 is negligible. The sign of phase shift depends upon the direction of signal flow. If the requirements of the switch were those of a

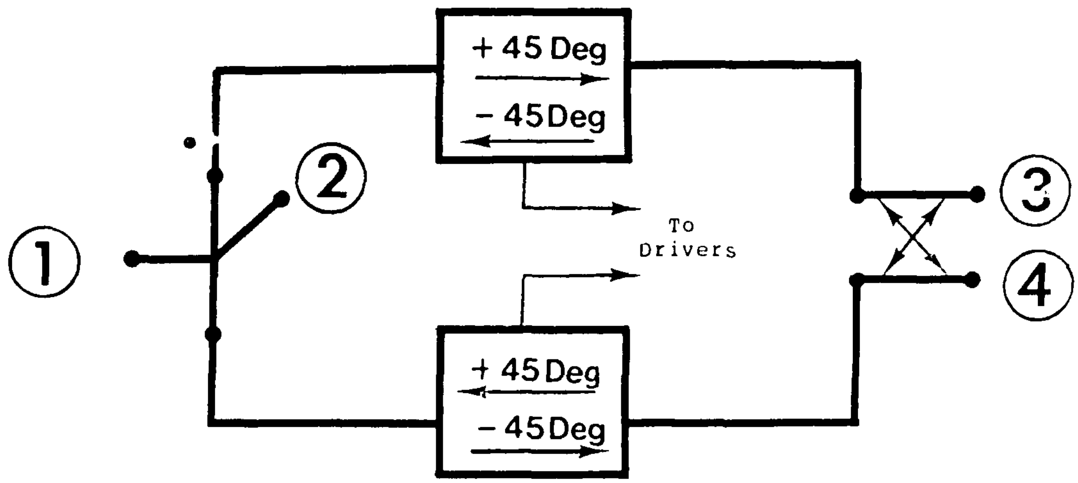

Figure 2. Four-port switchable circulator. Phase shifts shown correspond to input at Port 1 and output at Port 4. Signs of phase shifts are reversed when device is switched.

transmit-receive circulator, anti-reciprocity would allow the received radar pulse entering Port 3 to exit through Port 2, while the received radar pulse entering from the orthogonal polarization would exit through Port 1. There would be insignificant coupling between the ports attached to the receiver. However, under actual operating conditions the phase shifters do allow this to occur with a high degree of isolation. The amount of phase shift is not only a function of average power through the device, but is also slightly altered by the duration and amplitude of the peak power pulse. The switch designer attempts to ameliorate this situation by setting the phase shifter so that the optimum phase shift occurs midway through the pulse. During recepton, however, the phase shift is not further altered. Hence this switch must be reset just prior to transmission and just prior to reception. In some instances the reset time may preclude short-range observation.

An interesting exception to the ferrite switch is a diode switch known as a "bulk effect microwave window [21]." About 20 dB isolation with 100 kW peak power and 0.001 duty cycle has been demonstrated at X-band. This device, employed in a bifurcated waveguide, as discussed in the reference, could be scaled to S-band to provide a switch that would not require resetting prior to reception. The disadvantage of the device is its short available "on" time of 10 μsec. However, this time exceeds the usual 1 μsec pulse time of a non-chirp radar. Another form of diode switch was constructed by Atlantic Microwave, Inc., of Bolton, Mass., for the X-band radar at New Mexico Institute of Mining and Technology in Socorro, N. M. There the "transfer switch" resembles a balanced duplexer with the transmit/receive tubes replaced by two phase shifter assemblies. A PIN diode switches a phase inverter into or out of one arm of the microwave circuit, shifting the signal from one output port to the other.

7.3.3. Receiver

While polarimetric isolation is relatively easy to improve in the receiver, many sources of ampiltude and phase mistracking can exist. Some of these, which are independent of signal dynamics, can be corrected by proper placement and adjustment of phase and amplitude trimming assemblies. Other sources of phase and amplitude mistracking, which are dependent on the intensity of the received signal, are probably amenable to computer correction. A third category, mistracking that exists over the receiver passband, can only be corrected by careful selection of components and by close matching of the overall phase delay through the receiver channels. The significant contributor to this third category is the error introduced by the phase variation over the bandwidth of the IF filter, also known as group delay. In a frequency-modulated (chirp) radar, the phase distortion that occurs near the bandpass edges of the IF filter can impact the range sidelobes. In polarimetric radar this distortion can affect those calculations that utilize the phase differences between the received polarizations, such as the canting angle. The significance of this distortion has not been determined, but because of the magnitude of the phase change near the skirts of most IF filters, the designer might consider an alternative filter design.

The phase variation may substantially affect the results if a so-called "matched" filter is employed. The matched filter is used in an attempt to maximize the signal-to-noise ratio within the receiver and, as such, the received pulse fills the intermediate frequency (IF) filter, including the areas of greatest phase distortion. The distortion can be mitigated if a Bessell function IF filter is used, or if a higher signal-to-noise ratio is acceptable and the IF filter bandwidth is made substantially wider than that of the transmitted pulse.

Reduced polarimetric isolation or interchannel signal coupling only occurs at two locations within the receiver: at the local oscillator power division network and as radiation between improperly shielded cables. The former can be eliminated by reducing the VSWR at the ports of the power divider and by the inclusion of a few low power isolators in the network. Amplifiers to increase the local oscillator level are usually required in a multichannel receiver; they may also provide some additional isolation. Radiation between components can be almost eliminated by careful assembly. A thorough discussion of isolation improvement and component requirements to minimize phase and amplitude mistracking errors is given by Ussailis et al. [14].

7.3.4. Reflections

We have stressed that polarimetric isolation is strongly dependent on the isolation provided by the radio frequency switch and the polarizer assembly. The dominant cause of isolation reduction, other than phase shifter uncertainty discussed above, is from reflected energy that is returned to these components from mismatches and imperfections in the microwave package and the antenna. The subject of propagation on a transmission line and the measurement of forward and reflected energy, whether as complex reflection coefficient or as VSWR, is in many cases misunderstood. It will be assumed here, that the reader is moderately familiar with the terms and the theory of matching between two-ports. An excellent survey of the subject, written for the "intelligent layman," is given by Maxwell [22]. This survey also appeared in RCA Review.

Consider a circuit of a transmitter attached to an antenna through a typical polarizer, as shown in Figure 3. We shall review the effect of a mismatch between these elements and then add polarimetric components. Standing waves on a transmission line between a transmitter and an antenna do not introduce additional loss per se; in the case of the lossless line, almost any VSWR on the line that is matchable is tolerable. This is not the case when a lossy line or other absorptive device is introduced between a source and its load. Then energy is lost as the transmitted and reflected signals propagate on the line. For reasonably low levels of VSWR this loss is imperceptable; generally a VSWR of 1.5:1 or even 2.0:1 does not have to be further reduced for efficient radar operation. Reduction of VSWR beyond these levels is sometimes performed to maintain the proper operating characteristics of the transmitting tube. The attenuation of the transmitted signal afforded by these VSWR levels with total absorption of the reflected wave is only 0.2 and 0.5 dB respectively. Only in the case of the dual-channel polarimetric radar is a VSWR of this magnitude significant, as it causes the radiation of unwanted cross-polarization.

Cross-polarization, as a result of a mismatch between the antenna and the transmitter, occurs because of the polarizer. Most polarizers employed in meteorological applications use a microwave device known as a hybrid junction, or a device which behaves as a hybrid junction. An example of the latter is the sloped-septum polarizer employed in the AFGL radar [14]. The signal flow in the hybrid junction is similar to the signal flow of the four-port ferrite RF switch discussed above. Any reflection returning from the antenna to which the device is attached travels back toward the transmitter. In the case of the polarizer, the reflection is split so that half of the energy returns to the transmitter and the other half returns to the other polarizer input port. Should a mismatch exist at the second receiver port, an appropriate percentage of the energy is then reflected back to the antenna. Unfortunately, the second receiver port is also the transmitter port for the orthogonal polarization. Hence the reflected energy enters the antenna as cross-polarization.

Recall that for a differential reflectivity radar the second receiver port is terminated. However, any reflections from this termination due to a slight mismatch in the remainder of the microwave path between the termination and the polarizer will be radiated as cross-polarization.

Radiation of unwanted cross-polarization can be reduced by the removal of reflections between the polarizer and free space. Removal of reflections between

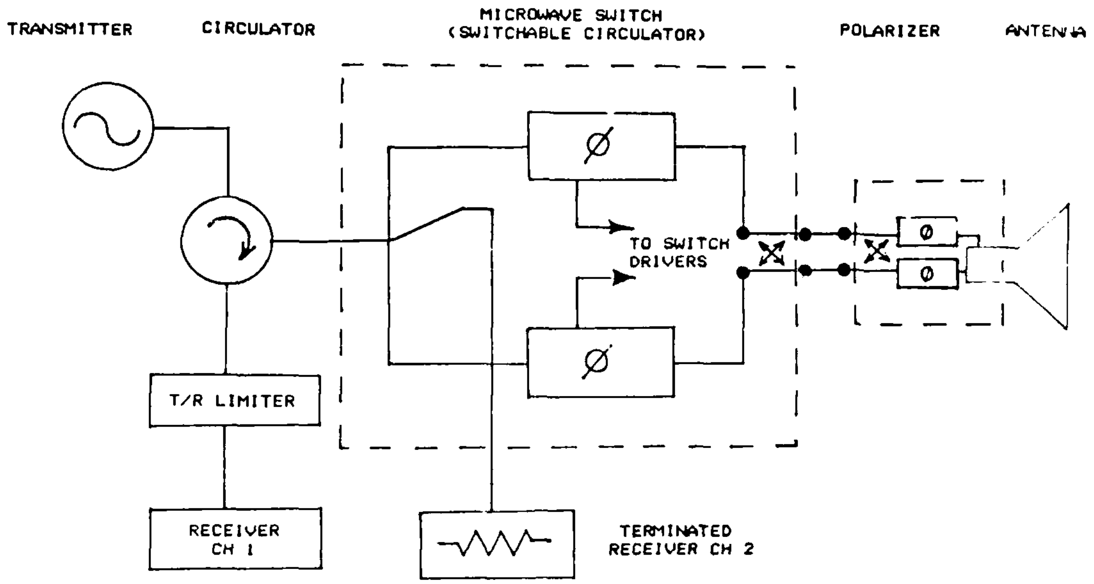

Figure 3. Typical microwave circuit used for measuring linear polarization differential reflectivity.

the transmitter and the polarizer is also necessary because normally energy is returned from the antenna to the polarizer. When the VSWR of all polarizer ports is approximately equal, the tolerable level of the residual VSWR is given by

$$VSWR = (1+|I|)/(1-|I|), \quad (2)$$

where I is the one-way isolation. Note that the parameter $|\Gamma|$, known in the literature as the "reflection coefficient," is identical to the one-way polarization isolation. Conversely, a given VSWR defines the polarization isolation of the system.

Hence, for a -26 dB one-way polarization a 1.1:1 VSWR is allowed between the polarizer and its attached components. Since the two-way polarization isolation is 6 dB less than the one-way isolation [12], this VSWR value will provide an observational isolation of -20 dB. For a -40 dB one-way polarization isolation a 1.02:1 VSWR is required; this value is extremely difficult to achieve over the bandwidth of the radar and is very difficult to measure.

7.3.5. Polarizer Matching: An Example

Consider a polarizer installed between a transmitter and an antenna feed. Reflections of forward energy are returned to the polarizer from every interface including waveguide junctions, bends, etc. For a single frequency of operation all the reflections entering the polarizer from the antenna may be canceled by introducing a "conjugate match" at the polarizer. In a conjugate match, the real parts of the mismatch are forced into equality, the imaginary parts are forced into the conjugate of each other [22]. A conjugate match presents a brick wall to the returned energy, in this case reflecting the energy back to the antenna before it enters the polarizer.

Since the hardware between the polarizer and the feed suffers from thermal expansion, a thermally stable conjugate match may not be fully achievable at a match point between the components. In any event, the best achievable conjugate match over a bandwidth comparable to that of the transmitted pulse must be installed and adjusted for minimum on-axis antenna cross-polarization. Residual reflections of the transmitted signal that are headed from the internal polarizer interfaces might be absorbed by the transmit-receive circulator, provided that an excellent match is also achieved between the waveguide, polarizer, and circulator. A reasonable alternative to this effort is to select components for the polarizer-transmitter interface that minimize the potential mismatch at that junction.

8. SUMMARY

We have attempted to dissect the polarimetric error concepts and explain them in terms of hardware performance. The pertinent equations have been discussed in the references at some length. However, the published detail may not be sufficient to determine all of hardware specifications in terms of polarimetric error quantities. For example, the one-way polarization term, f [12], was assumed to be the polarimetric isolation of differential reflectivity radar observing an ensemble of identical hydrometeors. Subsequently we determined that, for the observation of an ensemble of mixed hydrometeors, f is a composite error term containing antenna errors related to the radar viewing angle, integrated cross-polarization ratio, polarizer/switch isolation, mistrack error between horizontal and vertical polarizations, etc.

To permit the description of a meteorological polarimetric radar system in terms of specifiable hardware, we recommend the following:

* The presently available error analysis should be validated with actual data.

* A complete mathematical description of polarization isolation, amplitude and phase error should be performed for the case when the reflection on each port of the polarizer/switch assembly is unequal.

* Error analysis and hardware requirements of the optimal polarization radar should be determined for both descrete and meteorological targets.

* Effect of a radome on the antenna amplitude and phase pattern should be completed and validated.

* A detailed relationship between the error analysis terms and hardware specifications should be completed.

We hope that these comments will help radar designers and users of radar data to understand better some of the sources of measurement error.

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